Scientific Objective 5: Upper Atmospheric Waves

The purpose of scientific objective 5 is to study excitation, propagation, and dissipation of wave motions in the upper atmosphere. Scientific objective 5 is further divided into the four sections "Global Morphology of Mesospheric and Thermospheric Waves," "Wave Motions of All Scales from 80 to 100 km Altitude," "Global Morphology of Lower Mesospheric Waves Using OH Radical," and "Wave Motions of All Scales in Stratosphere and Their Sources."

Global Morphology of Mesospheric and Thermospheric Waves

Introduction.- The motion of the atmosphere above about 60 km can be described in terms of a prevailing wind, tidal oscillations, an irregular component due to internal gravity waves, and turbulence. The tidal and gravity wave fields contain as much energy as the longer time scale geostrophically balanced motions and make a major contribution to the global balance of energy and momentum at these heights.

The sources of the tidal oscillations are believed to be heating by absorption of solar radiation by ozone and water vapor (Butler and Small, 1963; Lindzen, 1967). However, the latitudinal variation of the diurnal and semidiurnal tides, the seasonal variations of these components, and the influence of the latitude variation of the mean wind and temperature on tidal wave propagation are far from understood; and studies of all these aspects require a greater world-wide observational coverage than is presently available. For gravity waves the identification of the source is more problematic since excitation by tropospheric interactions, by changes associated with the auroral electrojet, and by nonlinear interactions of tidal oscillations is expected to be capable of generating such waves. It is evident that information on the global morphology of atmospheric oscillations will also help to identify the roles of these different sources.

On the basis of studies of the propagation characteristics of extratropical planetary waves (e.g., Charney and Drazin, 1961), it would be expected that such waves will only propagate through the stratosphere and be detected at mesospheric heights in the presence of a relatively weak westerly flow. However, in view of the possible role of such waves in the transport of trace species, in addition to that arising from turbulent mixing, every attempt should be made to identify and study planetary scale structures in the mesosphere and at even greater heights.

Present status.- For the present heights of interest, the greatest contribution to the study of atmospheric tides has been made by meteor radar observations (e.g., Greenhow and Neufeld, 1961) but these have been limited to the 80 to 105 km height range. Greenhow and Neufeld have shown that the diurnal component of the tidal wind is dominant at low latitudes and the semidiurnal component is dominant at high latitudes (Spizzichino, 1969). Recent incoherent scatter observations at Arecibo by Harper (1977) have confirmed that the diurnal variation is dominant below 110 km but the semidiurnal component is strongest at 150 to 170 km. Amplitudes of both oscillations can reach 100 m/s at

100 km, with 30 km being a reasonable estimate for the vertical wavelength of the component.

For studies of gravity waves a number of ground-based techniques have been used. Radio and radar probing (Manson et al., 1976; Woodman and Guillen, 1974) and meteor drift studies (Geller et al., 1977) have all contributed to information on waves below about 105 km, as have observations of airglow emissions (Krassovsky and Shagaev, 1974). A major number of the disturbances observed at mesospheric heights are believed to originate at lower levels. At thermospheric heights, radio probing studies (e.g., Munro, 1950) have provided considerable information on traveling ionospheric disturbances, which represent the response of the F-region plasma to the driving force of gravity waves, under the control of the Earth's magnetic fields. There is considerable evidence to associate the disturbances of medium or large scales (100 to 1000 km wavelengths) with polar disturbances (Georges, 1967), but the generation mechanism is not established. Even at these thermospheric levels, a less coherent type of disturbance sometimes observed is believed to originate at lower levels (Georges, 1968).

Relevance to lidar.- Series studies of atmospheric tides at the heights of interest by lidar techniques have been limited to the work of Kent et al. (1972). This was based on the fluctuations of molecular densities measured by Rayleigh scattering using a very sensitive system.

A number of ground-based systems have been used to observe the mesospheric sodium layer using resonance scattering. These have operated with vertical pointing laser beams and have commonly shown large variations in the shape of the vertical height distribution in a single night (e.g., Sandford and Gibson, 1970); in these variations a downward propagating wave has been identified (Blamont et al., 1972; Rowlett et al., 1978). In addition, observations with a steerable beam have shown the presence of small scale structure and also a horizontal variation over distances of about 80 km, such a variation persisting for over an hour (Thomas et al., 1976 and 1977).

For thermospheric levels, metal atoms and ions provide suitable tracers for studies of motions. However, resonance scatter from these constituents occurs at ultraviolet wavelengths and this approach has not been possible from the ground because of atmospheric absorption of these wavelengths.

A comparison of the horizontal structures of sodium and neutral magnesium will provide information on the vertical phase progression of gravity waves. Furthermore, a similar comparison of the neutral and ionized magnesium measurements for as high an altitude in the lower thermosphere as possible will demonstrate the influence of the Earth's magnetic field on traveling ionospheric disturbances commonly observed by radio techniques.

The extension of the measurements to yield height profiles will reduce the horizontal resolution but will also provide information on the vertical phase progression of waves. Thus, for the sodium layer the horizontal resolution expected for profile data will be about 50 km in daytime, but this will still be sufficient to observe the larger gravity wave structures and those arising from tidal oscillations and planetary waves. The combination of the sodium and neutral magnesium height profiles could provide detailed information over the

80 to 180 km region to enable vertical wavelengths for gravity waves (10 km), tides (30 km), and also planetary waves to be identified. The measurement of the Mg^+ profile within sporadic E-layer would enable the downward transport of metal ions by gravity waves to be recognized.

Wave Motions of All Scales From 80 to 100 km Altitude

Introduction.- It is expected that in the 80 to 100 km height range the major wave phenomena and effects will arise from gravity-wave and tidal-scale disturbances. On the basis of theoretical predictions, the amplitudes of planetary-scale disturbances will be small because of interactions with the zonal wind field at stratospheric heights (Charney and Drazin, 1961), but these effects might still be important especially in the transport of trace constituents.

For tidal oscillations and gravity waves originating at lower heights, it is expected that the perturbations increase with height as $\rho^{-1/2}$ (where ρ is mean density), but this growth is countered at the upper levels of the present heights of interest by enhanced dissipation arising from large values of kinematic viscosity and thermal conductivity. Such dissipation is believed to be responsible for a significant heating at these and higher levels (Hines, 1965). Marked attenuation of gravity waves can also be seen at critical levels where the horizontal phase velocity is equal to the velocity of the mean wind (Booker and Bretherton, 1967). The transfer of moment of momentum to the wind at such levels can influence the atmospheric circulation (Jones and Houghton, 1971), and nonlinear interactions can give rise to turbulent layers at such levels (Fritts, 1978). The generation of turbulence by gravity waves and tidal oscillations in the present height of interest is of considerable interest both in relation to small-scale accuracy of atmospheric constituents (Lindzen, 1971) and also in controlling the circulation at these levels (Houghton, 1978).

Present status.- The information currently available on wave motions in the 80 to 100 km region has been derived largely from ground-based techniques. The meteor radar method has made a major contribution to tidal studies in recognizing the predominance of the diurnal component at low latitudes and semidiurnal component at high latitudes (Spizzichino, 1969) and has demonstrated that the amplitudes of each component can reach 100 m/s at 100 km. This approach has also been used to identify some of the characteristics of gravity waves and has also identified longer term oscillations which have been attributed to planetary waves. Very-high-frequency Doppler radar measurements have illustrated the propagation of gravity waves to mesospheric heights from below (Woodman and Guillen, 1974) and have shown a growth in amplitude and dissipation with increasing height. The influence of gravity waves in the 80 to 100 km region has been demonstrated in airflow observations of intensities and temperatures (Krassovsky and Shagaev, 1974). Recent results of Noxon (1978) have revealed very large temperature oscillations which will facilitate the observation of such waves but will also demand a nonlinear treatment in investigations at these heights.

Relevance to lidar.- Because of the relatively small molecular densities existing in the 80 to 100 km region, Rayleigh scattering does not lend itself

readily to studies of wave motions at these altitudes, although some results on tidal oscillations have been obtained using a large, sensitive receiving system (Kent et al., 1972). In contrast, observations of the mesospheric sodium layer by resonance scattering have successfully demonstrated gravity-wave activity. Large variations have been observed in the vertical height distributions (e.g., Sandford and Gibson, 1970), and evidence for a downward propagation wave has been found (Blamont et al., 1972). In addition, measurements of profiles at two points separated by about 15 km have shown oscillations similar to those expected for gravity waves, and evidence for a horizontal variation over distances of about 80 km has been obtained (Thomas et al., 1976 and 1977); if this variation is attributed to wave action, its persistence of about an hour would seem to imply a standing-wave pattern.

These results indicate that the detailed height information available from lidar experiments combined with the latitude coverage provided by a satellite experiment could provide the necessary information for the present wave studies.

The development of the ground-based method for studying the mesospheric sodium layer provides the best basis for lidar measurements of waves in the 80 to 100 km region; Rayleigh scattering studies for this height range will not be feasible. Further development will be directed towards the incorporation of temperature measurements from observations of the Doppler broadening of the sodium line profile and of wind measurements from the Doppler shift imposed on this profile.

Global Morphology of Lower Mesospheric Waves Using OH Radical

Introduction.- As with the lower thermosphere, the 60 to 80 km height region should contain disturbances of gravity-wave, tidal-oscillation, and planetary-wave scales. However, for gravity waves and tides the amplitudes at the lower heights will be reduced in proportion to ρ^{-1} (where ρ is mean density) and will, therefore, be more difficult to detect. Thus, direct observations of these waves at a 60 km height, based on temperature or wind measurements, will require accuracies of about 1 K and 2 m/s, respectively. For planetary waves, the amplitudes should be larger in the 60 to 80 km region than in the lower thermosphere, but the above measurement accuracies will still be required.

The 60 to 80 km height range is of interest because, on the basis of present ideas, it does not represent a major source region of waves and is still below the region of major dissipation of gravity waves and tides.

Present status.- The study of atmospheric waves in the 60 to 80 km height range has not attracted the same attention as at other heights. Observations with rocketsondes have terminated at the lower height limit, and the meteor radar technique can only provide information above 80 km. Some information on motions in the upper part of the height range has been given by observations of partial reflections of MF radio waves pulses (e.g., Manson et al., 1976), and large VHF facilities (e.g., Woodman and Guillen, 1974) are particularly useful for observations of the smaller-scale disturbances. Information on planetary waves has been provided since 1975 by measurements of temperature structure

using the Pressure Modulator Radiometer and the Limb Radiance Inversion Radiometer on a Nimbus 6 satellite, and such instruments could in the future be also used for wind measurements.

Relevance to lidar.- Observations of the 60 to 80 km height region of the atmosphere are rendered difficult by the absence of any suitable scattering constituent. Rayleigh scattering has been used for observing tidal oscillations (Kent et al., 1972) but has required a very sensitive system.

Both theoretical (Thomas and Bowman, 1972) and experimental treatments (Anderson, 1971a and 1971b) have indicated concentrations of the OH radical in excess of 10^6 cm^{-3} at heights between about 60 and 75 km, the concentration decreasing rapidly with further increase in height. No lidar observation of this constituent has been made at these heights. However, it can be shown that resonance scattering of lines in the OH ($^2\Sigma$ - $^2\Pi$) band system near 300 nm will exceed Rayleigh scattering; and when account is taken of quenching of the $^2\Sigma^+$ state, it is found that the scattering efficiency is greater than 80 percent above about 60 km. Thus the OH radical could provide a suitable tracer for studying the 60 to 80 km region by a lidar technique.

Wave Motions of All Scales in Stratosphere and Their Sources

Introduction.- Although a number of atmospheric oscillations are expected at stratospheric heights, some of these do not lend themselves to observations during Spacelab flights limited in duration to one or two weeks. They include the annual periodicity, the quasi-biennial oscillation commonly observed below 35 km, the semiannual oscillations most evident above this height, and the periodicity of about 14 days observed in the amplitude of planetary waves. Thus the present consideration of Spacelab observations of the stratosphere will be confined to planetary waves, gravity waves, and tides. However, future operations with a power module might make the observation of some longer-term oscillations possible.

For planetary waves, it is considered that the differential solar heating over oceans and continents dominates the production of waves in the middle stratosphere, with wind flow over orographic features being capable of generating waves at lower heights (Beer, 1974). A study of planetary-wave activity at a series of heights in the stratosphere in relation to the distribution of continents, oceans, and mountain ranges might help identify these sources, as well as the role of baroclinic instability in the excitation of waves at heights above about 30 km.

For gravity waves, the lee waves generated by the passage of winds over extensive chains of mountains provide specific sources capable of study from world-wide observations of the stratosphere. Furthermore, the production of such waves by the supersonic movement of the terminator should be more easily detectable at stratospheric heights than at ground level.

For both types of waves, interaction with the mean flow is known to be of major importance. In particular, the presence of critical layers, in which the horizontal phase velocity is equal to that of the mean wind (e.g., Booker and

Bretherton, 1967), can cause marked attenuation. Consequently, the interpretation of changes in the wave amplitudes with height will need to take account of this effect as well as the possibility of reflection from features in the wind and temperature profiles.

For tidal oscillations, the sources mechanisms are believed to be heating caused by absorption of solar radiations, of ozone in the upper stratosphere (Butler and Small, 1963), and of water vapor at lower heights (Lindzen, 1967). The detection of tidal oscillations at stratospheric heights will be relevant to the confirmation of these ideas.

Present status.- The greatest information on atmospheric waves at stratospheric heights probably relates to planetary scale effects. Hirota (1975) and Hirota and Sato (1969) have shown that traveling waves of few meters per second amplitude in summer, and considerably larger amplitude in winter, are frequently observed; and corresponding temperature fluctuations have been detected from Nimbus satellites in summer (about 1 K) and winter (about 10 K). The planetary-wave effects associated with stratospheric warmings can be considerably larger (Labitzke, 1972).

Both theoretical and experimental studies on tidal oscillations at stratospheric heights have indicated small amplitudes. Thus for the diurnal component, Reed et al. (1969) have shown from observations and Lindzen (1967) from theoretical analysis that an amplitude of 1 m/s is representative of 30 km altitude.

Similar small amplitudes are also to be expected for gravity waves. According to the results of the meteorological rocket network (Justus and Woodrum, 1973) and measurements with VHF radar (Woodman and Guillen, 1974; Rüster et al., 1978), amplitudes less than 1 m/s are to be normally expected near 20 km.

It is evident that the detection of such small changes in wind or temperature for studies of the wave field at stratospheric heights will be very challenging.

Relevance to lidar.- The objective of examining planetary wave activity at different heights in the stratosphere, in order to identify the proposed source mechanisms, could be realized with the good height resolution characteristic of the lidar technique. This feature could also lend itself to the identification of vertical wavelengths of atmospheric oscillations in the stratosphere.

To date, no lidar observations of the wind field, or of the detailed temperature structure, at stratospheric heights have been reported. The measurement of the Doppler shift imposed on laser radiation from moving atmospheric aerosols has been demonstrated for tropospheric heights by Benedetti-Michelangeli et al. (1972). Their experiment made use of a stabilized, chopped argon ion laser operating at 633.8 nm with photon counting being used in the receiver system. In addition, the general capability of a coherent infrared lidar technique for accurate wind measurement has been demonstrated by Huffaker, 1975.

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